Challenges of Liquid Scintillator (water-based & Metal-loaded) for Physics Frontiers

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BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

U.S. DEPARTMENT OF ENERGY | Office of Science

Joint CPAD and IF Meeting ANL, Jan. 2013

Detector R&D Program

- *prioritize the resources to optimize the impact on the HEP program.*
- *reduce duplication in detector R&D efforts*
- *identify new areas in which detector R&D funding can impact the HEP program*

Instrumentation Frontier

Detector System of Liquid Scintillator (Metal-loaded & Water-based)
- M. Yeh and J. Klein

Intensity Frontier

(neutrino physics & nucleon decay): LBL & SBL reactor-ν, $0\nu\beta\beta$, pDk^+, other physics, etc.

Energy Frontier

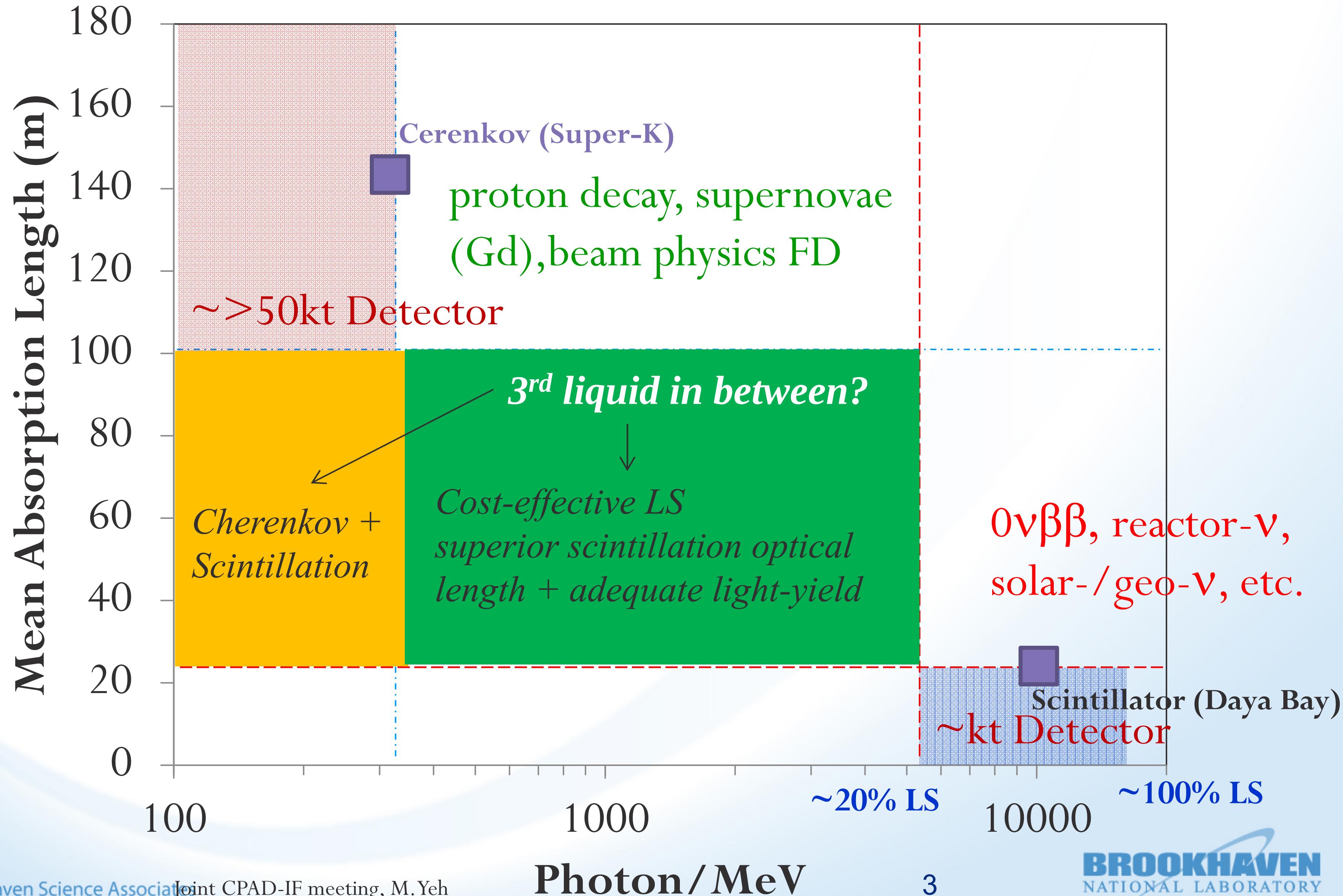
(collide physics)
Calorimetry

Cosmic Frontier

(dark-matter)
Active Veto system

Liquid Scintillation Detector R&D programs for the scientific needs of the Energy, Intensity, and Cosmic Frontiers.

Cherenkov and Scintillation Detectors



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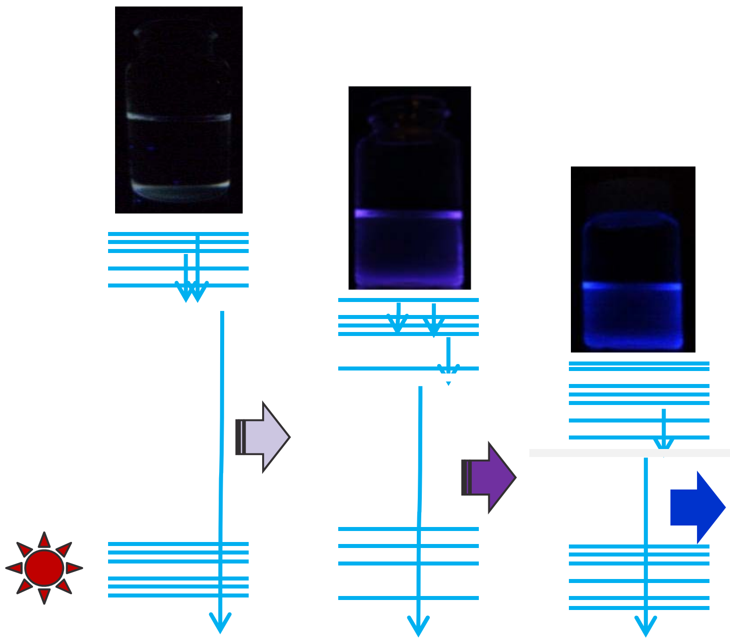
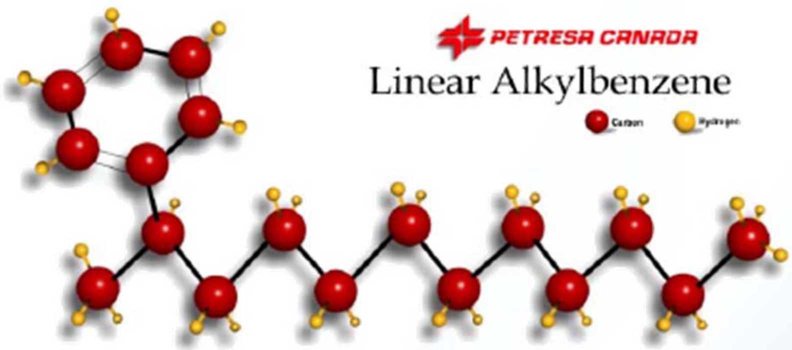
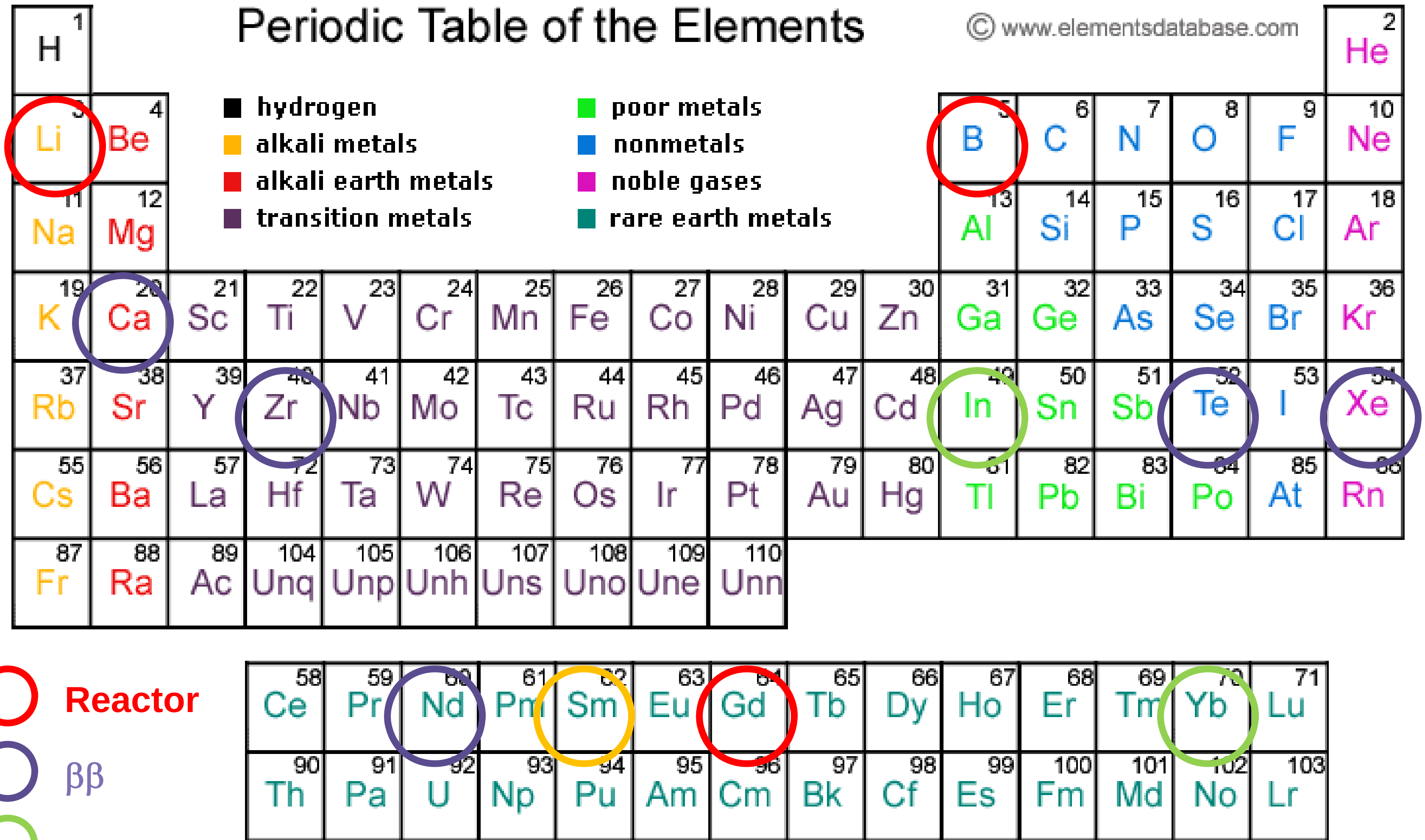




Current Knowledge of Liquid Scintillator

Metal-loaded LS for a variety of physics expt’s



Reactor

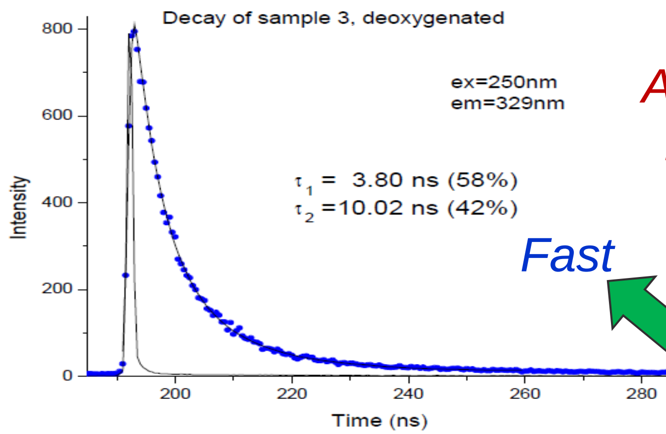
ββ

Solar

Others

Linear Alkylbenzene is the new favor for LS (R&D by SNO+)

New Water-based LS (Cherenkov+Scintillation)



Fast

A cost-effective option for large detector as source, detection or veto

Stable

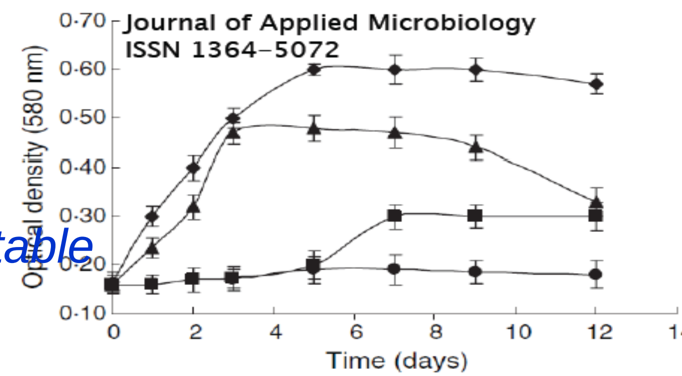
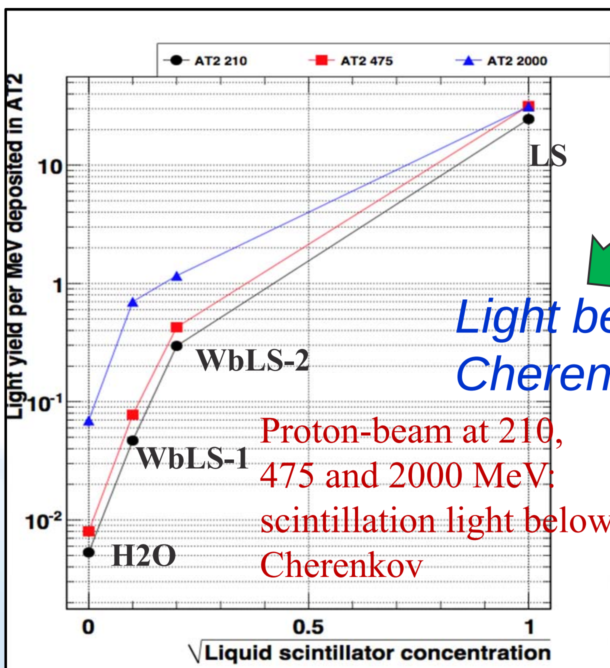


Figure 5 Time-course analysis of consortium growth at different linear alkylbenzene sulfonate concentrations (in mg l^{-1}): (◆) 10; (▲) 20; (■), 50; and (●) 100. Values are means ± standard deviations for three replicates.

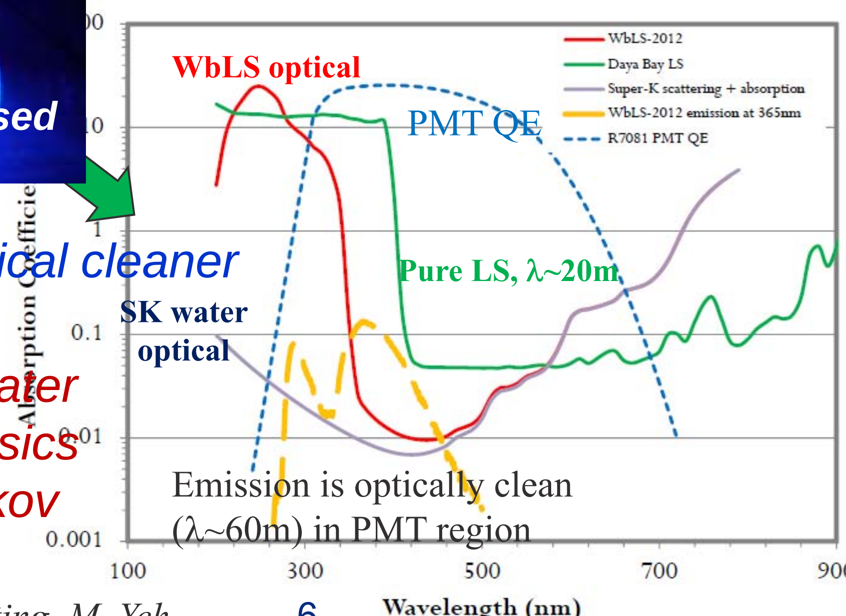
A new water-based scintillator



Light below Cherenkov

A scintillating water that probes physics below Cherenkov

Optical cleaner



- *Neutrino Physics*
- *Double-beta Decay*
- *Nucleon Decay*

Liquid Scintillator for Intensity Frontier

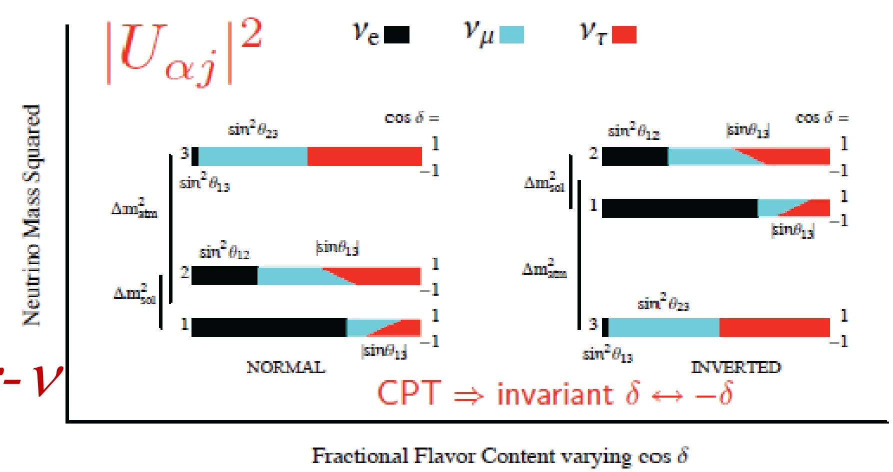
Remaining unknowns of ν-sector

Atm. dom. | Atm. subdom. | Solar | Majorana

$$U=\begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\times\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta}\\0&1&0\\-s_{13}e^{i\delta}&0&c_{13}\end{pmatrix}\times\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}\times\begin{pmatrix}e^{i\alpha_1/2}&0&0\\0&e^{i\alpha_2/2}&0\\0&0&1\end{pmatrix}$$

- How large is the CP phase? } *LBNE*
- Is neutrino a Majorana particle?
- Is neutrino mass hierarchy normal or inverted? } *reactor-ν*

$0\nu\beta\beta$ {

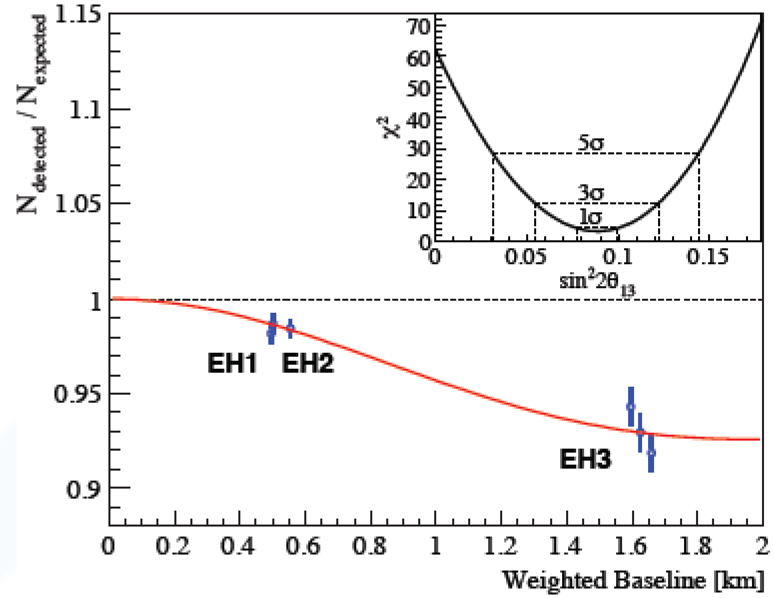


The known, large θ_{13} allows us to define future program

Long Baseline (LBL) Reactor Neutrino

$$P_R(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - \begin{Bmatrix} \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \\ +\sin^2 2\theta_{13}\sin^2\theta_{12}\left(\cos 2\Delta_{31}\sin^2\Delta_{21} - \tfrac{1}{2}\sin 2\Delta_{31}\sin 2\Delta_{21}\right) \end{Bmatrix}$$

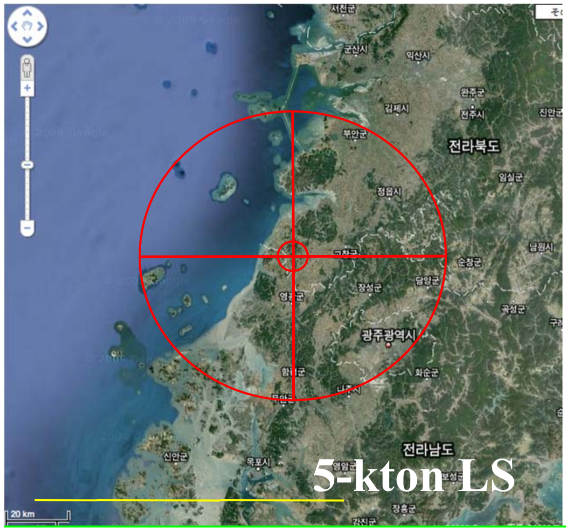
- *Simpler formula than accelerator experiment and no CP-dependence.*
- *Rich physics programs*
  - ***Mass hierarchy***
  - ***Precision measurement of 4 mixing parameters***
  - *Supernovae neutrino, Geo-neutrino, Atmospheric neutrino*
  - *Exotic searches*



Daya Bay

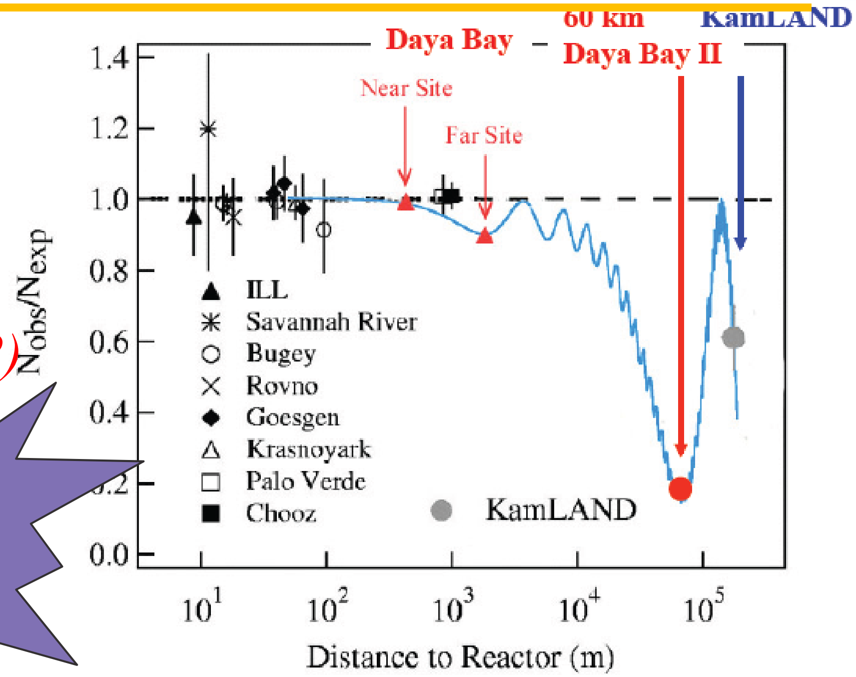
$\sin^2 2\theta_{13}$ = 0.089 ± 0.010 (stat) ± 0.005 (syst)

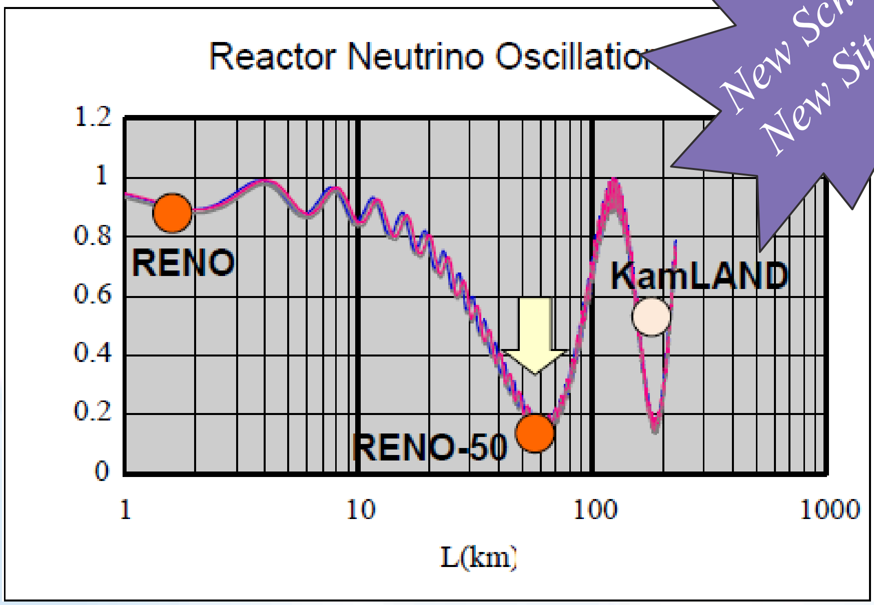
Daya Bay II vs. RENO-50



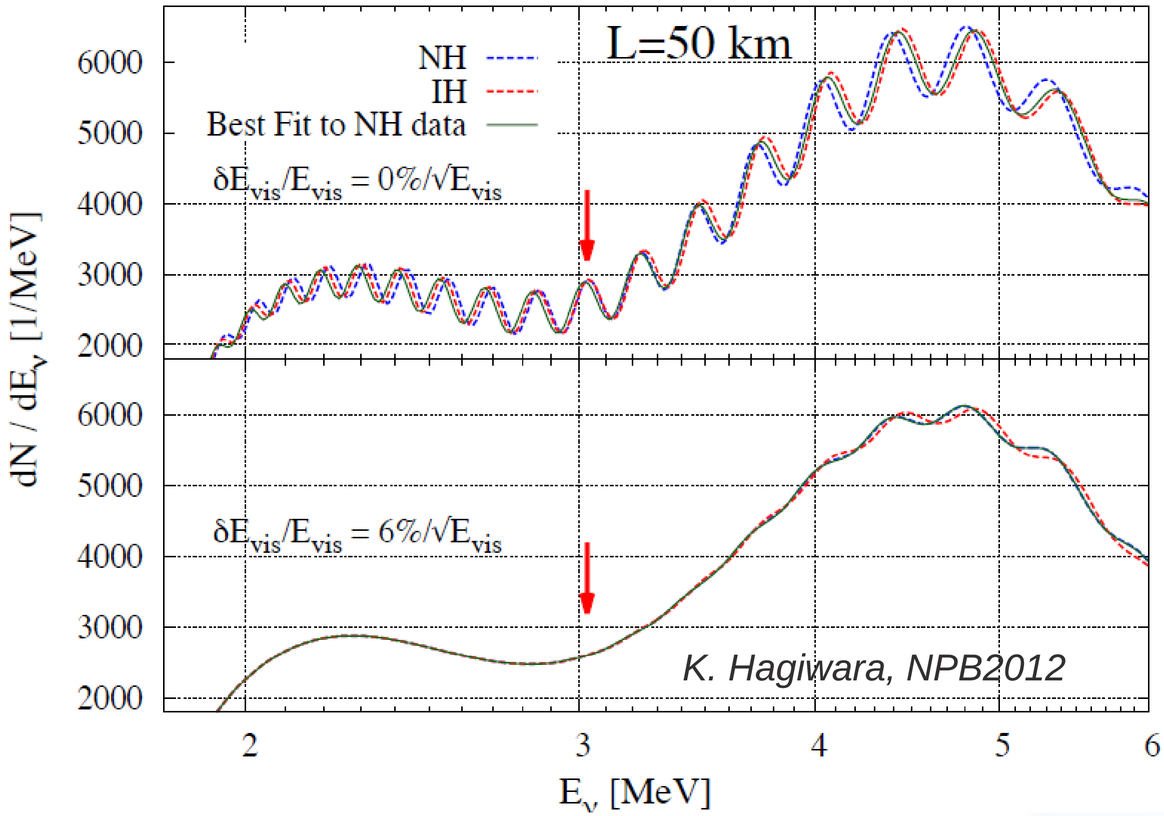
DayaBay-II plans to submit the proposal in 2015 and to start the construction in 2016. (summer 2012)

New Schedule and New Site as NOW





Challenge: Energy Resolution



- *Two different oscillation frequencies; but small! A very challenge expt.*
- *A nice summary of challenges by X. Qin et al., arXiv: 1208.1551X.*

<u>Need better than 3% resolution (more photo-electrons)</u>

- *high transparent (×1.9) & light-yield LS (×1.5)*
- *High QE PMT & photo-coverage* *LAPPD*

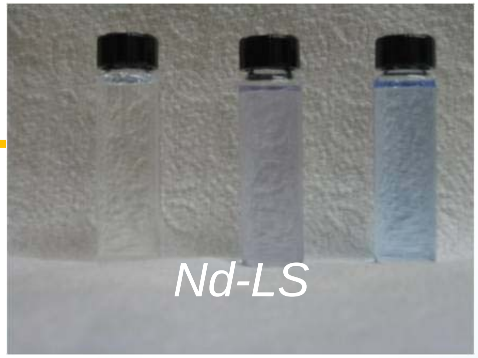
This type of liquid scintillator does not appear on the radar screen yet:

- *New scintillator R&D*
- *Large stoke-shift fluor*

X. Qin et al., arXiv: 1208.1551X.

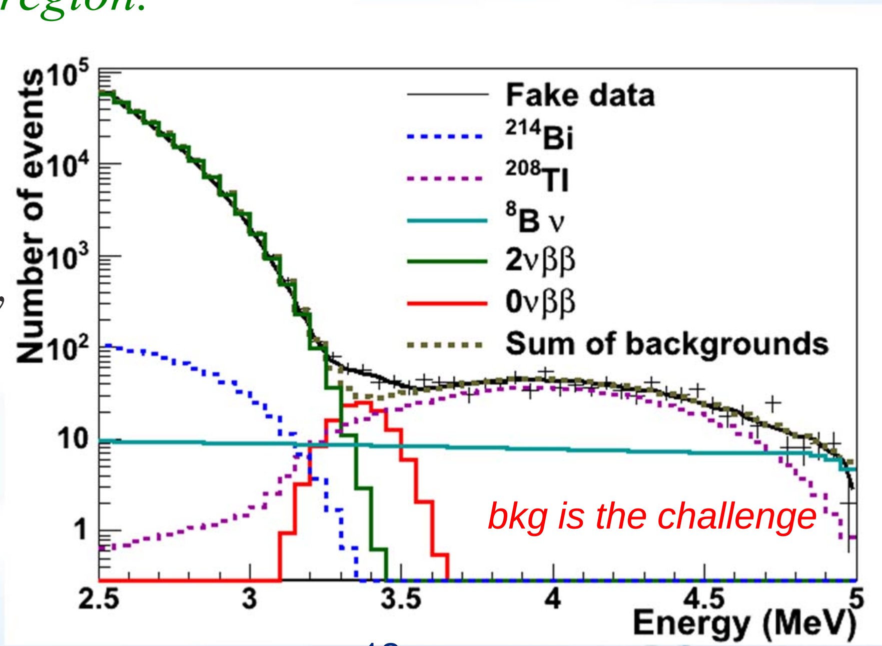
Double-beta Decay

Isotope	G^{0v} ($\times 10^{-15}$ y^{-1})	Q-value (MeV)	Abundance %
^{48}Ca	75.8	4.27	0.2
^{76}Ge	7.6	2.04	7.8
^{82}Se	33.5	3.00	9.2
^{76}Zr	69.7	3.35	2.8
^{100}Mo	54.5	3.03	9.6
^{116}Cd	58.9	2.80	7.5
^{130}Te	52.8	2.53	34.5
^{136}Xe	56.3	2.48	8.9
^{150}Nd	249.0	3.37	5.6



Searching for $0\nu\beta\beta$-decay to answer:

- *whether neutrinos are Dirac or Majorana particles*
- *probe neutrino masses at the hierarchy region.*

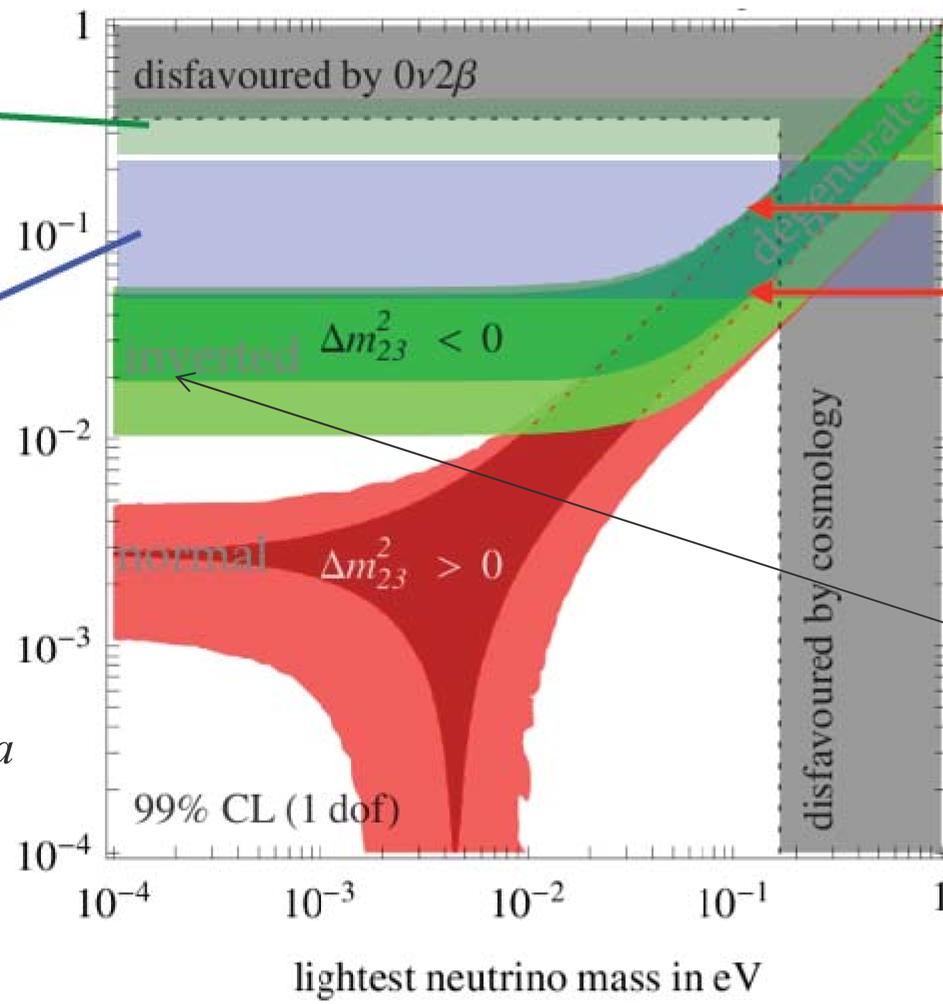


- *Scintillator-based detector has flexibility and scalability (without rising cost except material itself).*
- *Limited by the source itself (e.g., Nd at 0.3% is optimized.*
- *Enriched- or New-isotope?*

Challenge: DBD Target Mass

Current Experiments
NEMO3, Cuoricino,
Gerda-I, SuperNEMO
demonstrator

Future Experiments
CUORE, EXO, GERDA,
SuperNEMO...



SNO+
stage 1

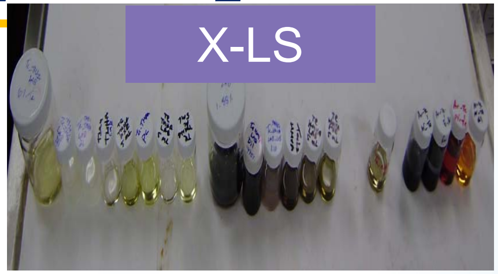
SNO+
stage 2:
enriched Nd

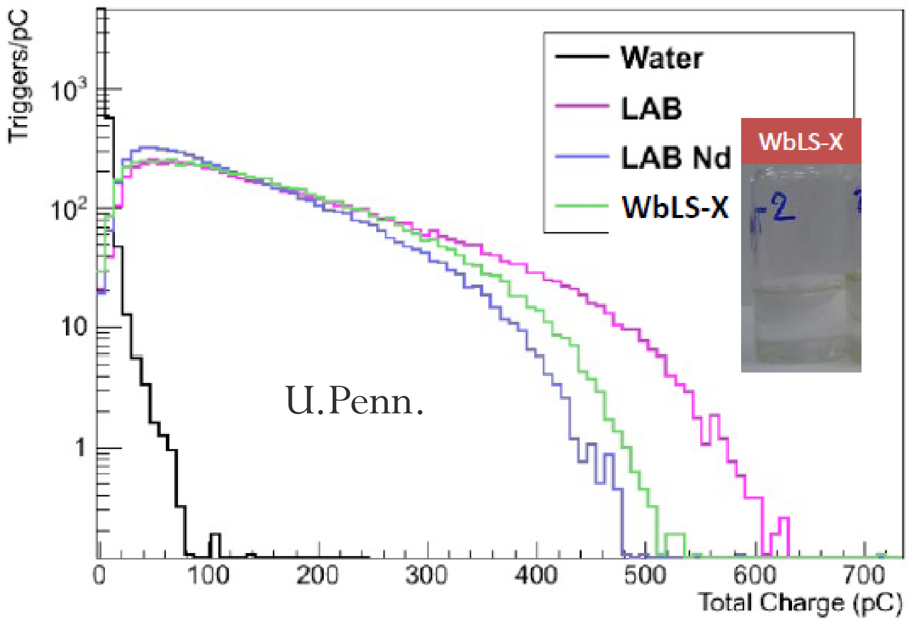
Can we probe the hierarchy region?

- *A $m_{\beta\beta}$ limit of ~20 meV would exclude Majorana neutrinos in an inverted hierarchy.*

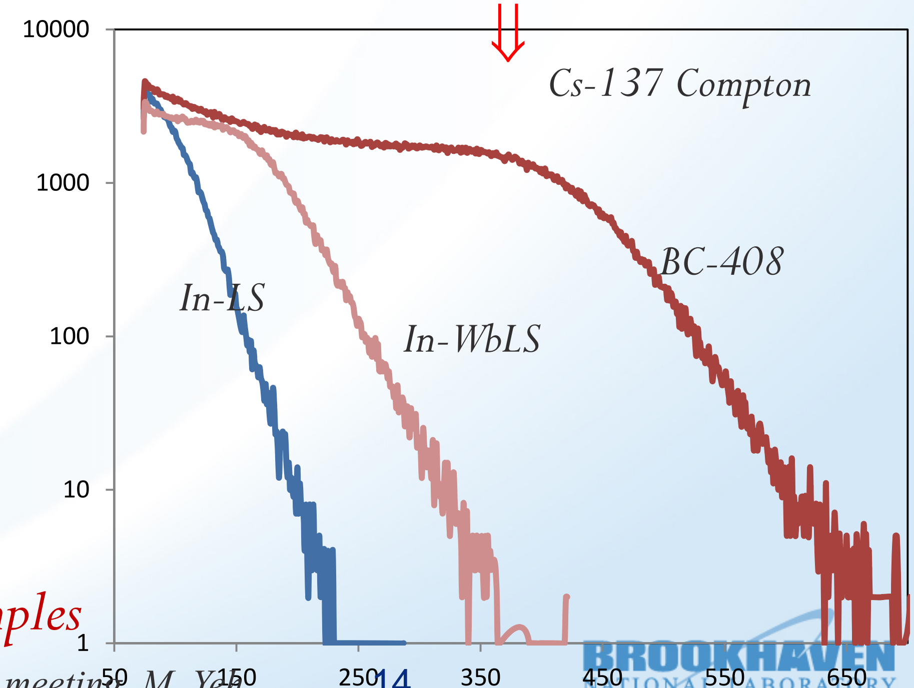
New metal-loading using WbLS principal

- *WbLS-X loading is faster and higher efficiency (ε=100%)*





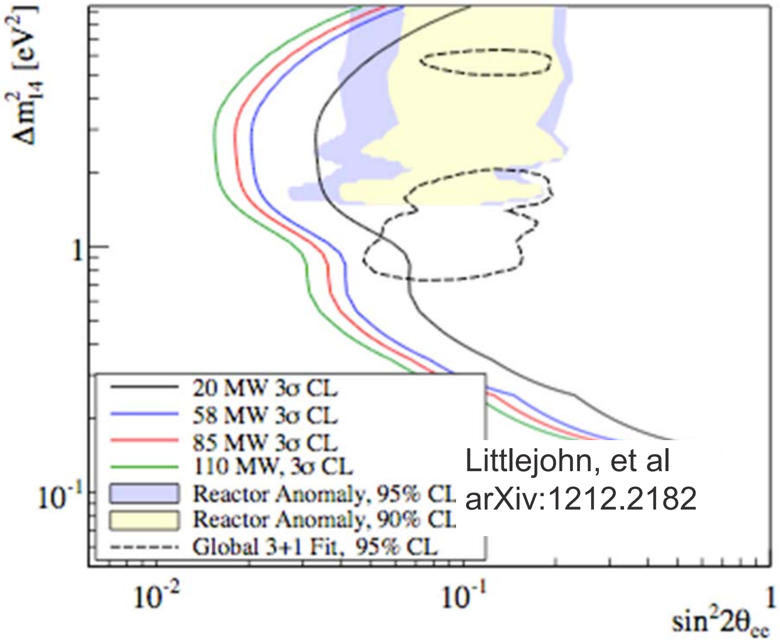
- *The M-WbLS has 20% higher light-yield than the Nd-LS (and optically better).*
- *The light-yield improves by ×2 for ~6% Indium-loaded LS*



- *A new loading technology for metallic ions that cannot be loaded before; extends the scientific reach.*
- *Better cocktails for environmental aqu. samples*

Short Baseline (SBL) Reactor Neutrino

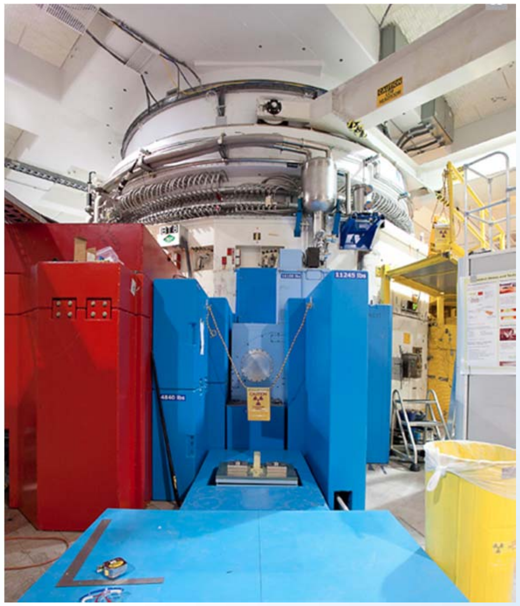
Test Reactor Anomaly and Sterile Neutrinos Hypothesis



Littlejohn, et al
arXiv:1212.2182

probe oscillation at
3σ in 1 year
5σ in 3 years

US has high-power US research reactors (e.g. ATR, HFIR, NIST)



Scientific Opportunities

- precision studies of reactor antineutrino spectra
- search for very short baseline oscillations and new physics
- test reactor anomaly & sterile ν

Detector Development

- **scintillators for neutron detection** and **PSD** (Gd vs. Li-doped, LAB vs. water vs. plastic)
- **background rejection techniques**
- **on-surface antineutrino detectors** with minimum overburden

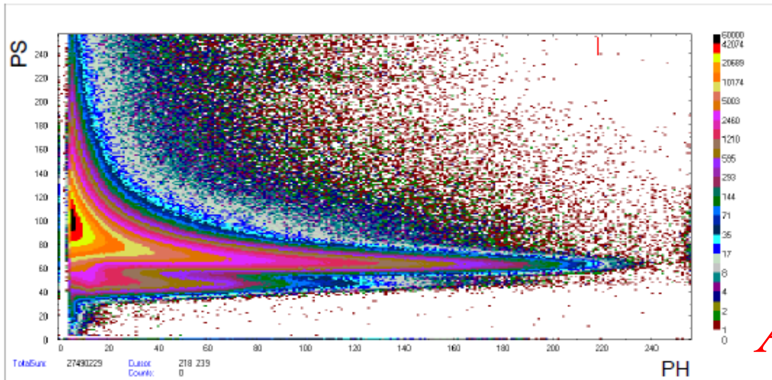
K. Heeger

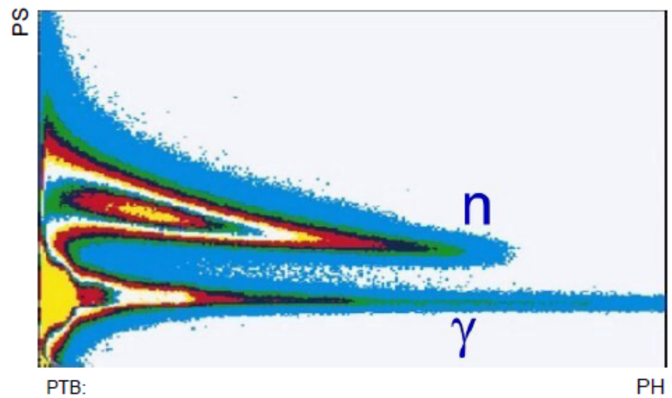
Pulse Shape Discrimination

Beam Data: Pulse Shape Discrimination

TECHNISCHE UNIVERSITÄT DRESDEN

PSD to separate events induced by γ and n





PTB:
http://www.ptb.de/en/org/6/65/n_g_spektr_details.htm

LAB + 2g/L PPO + 15mg/L bisMSB

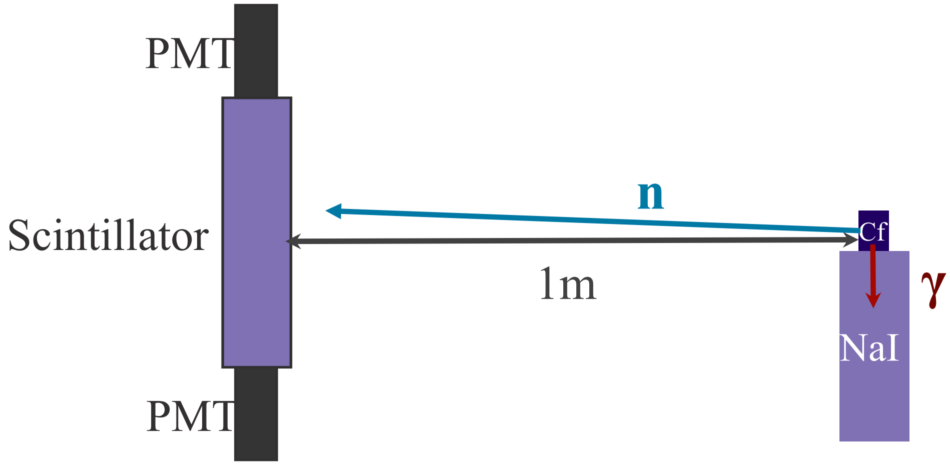
A new hybrid liquid scintillator?

NE213

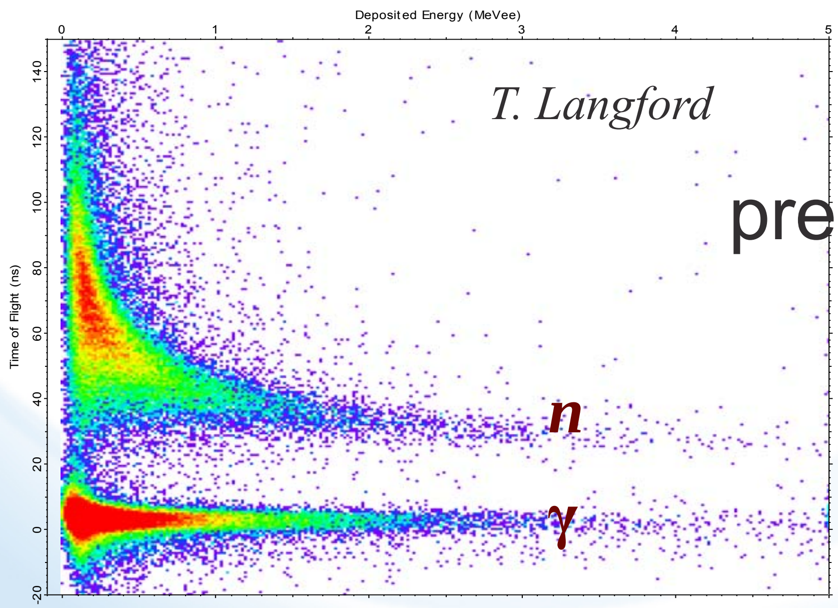
xylene-based LS; specially designed for fast neutron measurement; not suitable for large detector

NIST nTOF Setup

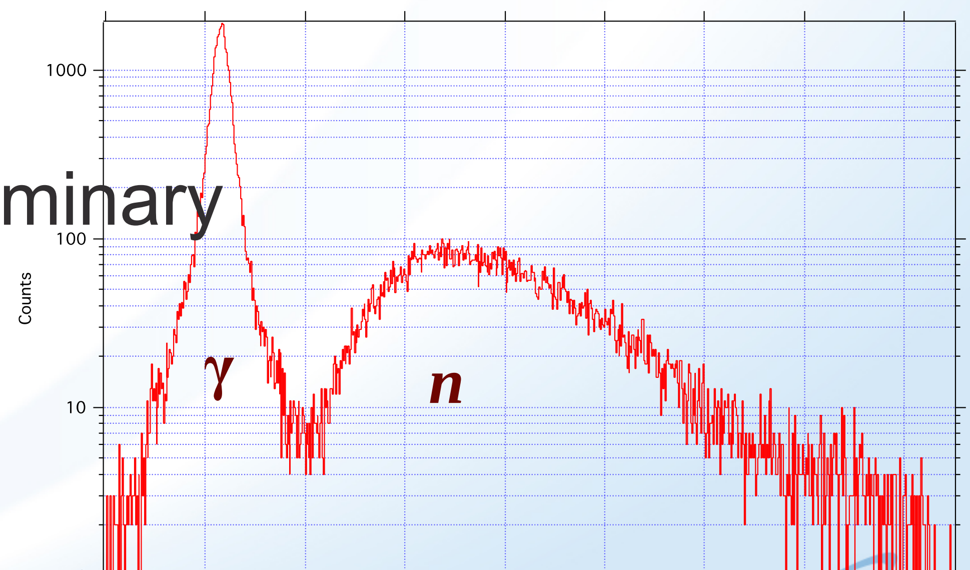
National Institute of Standards and Technology
U.S. Department of Commerce



- *A national facility with expertise in neutron detection.*
- *Capable of testing (n,γ) PSD for a variety of liquid scintillators.*
- *A key player in Li-loaded LS.*

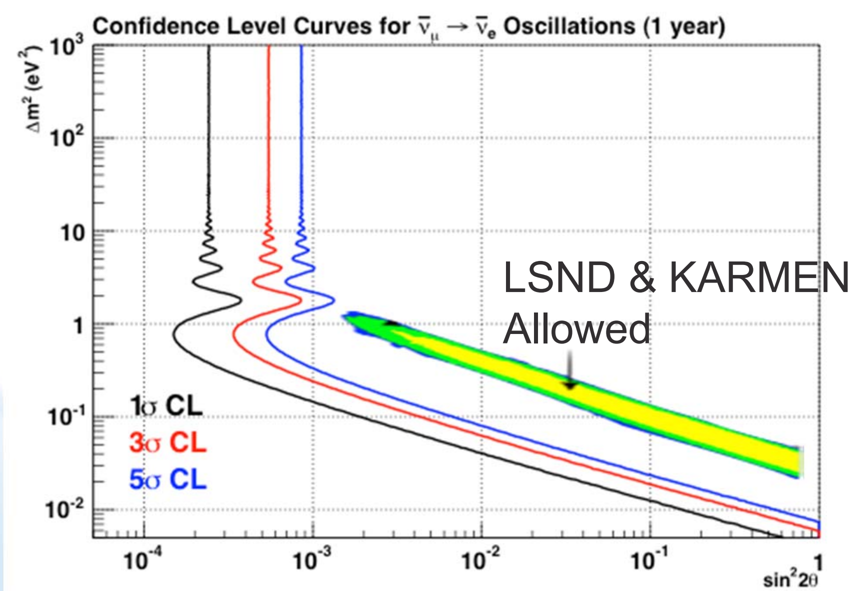


preliminary



Sterile-ν (non-source-based) by OscSNS

- *Prove or disprove the existence of sterile neutrinos by comparing NC reactions in near and far detector and by observing oscillations in the detector of CC & NC reactions*
- *Short baseline $\bar{\nu}_e$ appearance*
- *Short baseline ν_e and ν_μ disappearance*



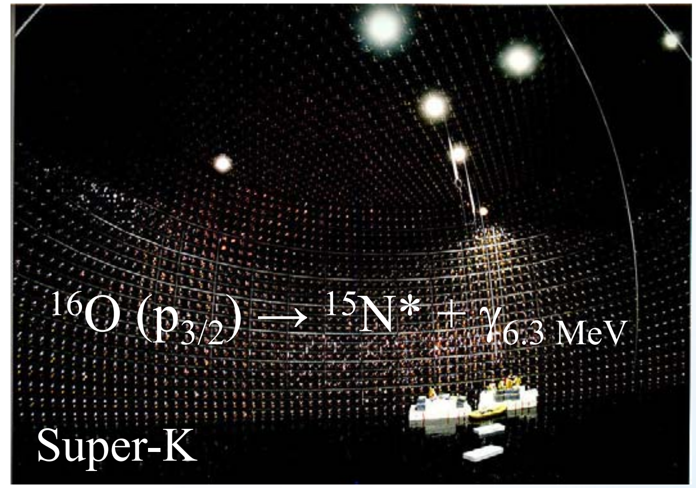
W. Louis

- *Cylindrical tank 8m dia.$\times$ 20.5m long; Total mass = 886 tons of oil (CH_2).*
- *Fiducial volume 6m dia.$\times$18.5m long; Fiducial mass = 450 tons of oil (CH_2).*
- *Detector located ~60m from ν source; surrounded by ~3240 8-inch PMTs.*
- *~10K ν events per year.*

Add Gd to enhance the $\bar{\nu}_e$ signal? Non-trivial for a MO (CH_2) system.

Proton Decay

- *SUSY SU(5) model predicts the pDK$^+$ mode to be dominant with a lifetime of $10^{29\text{-}35}$ yrs.*
- *LBNE-II, Hyper-K?*
- *Will there be a cost-effective option?*



$$\tau(p \rightarrow k^+\bar{\nu}) > 2.3\times10^{33}\,\text{yrs}$$

- *Challenges of*
  - *large target mass (proton): water Cherenkov detector is the most cost-effect option to reach the sensitivity.*
  - *T_{K+} ~105 MeV is below Cerenkov threshold*
  - *Atmospheric ν_μ-induced μ^+*

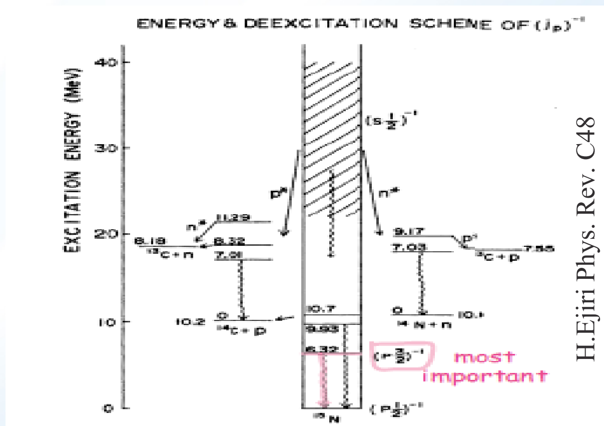
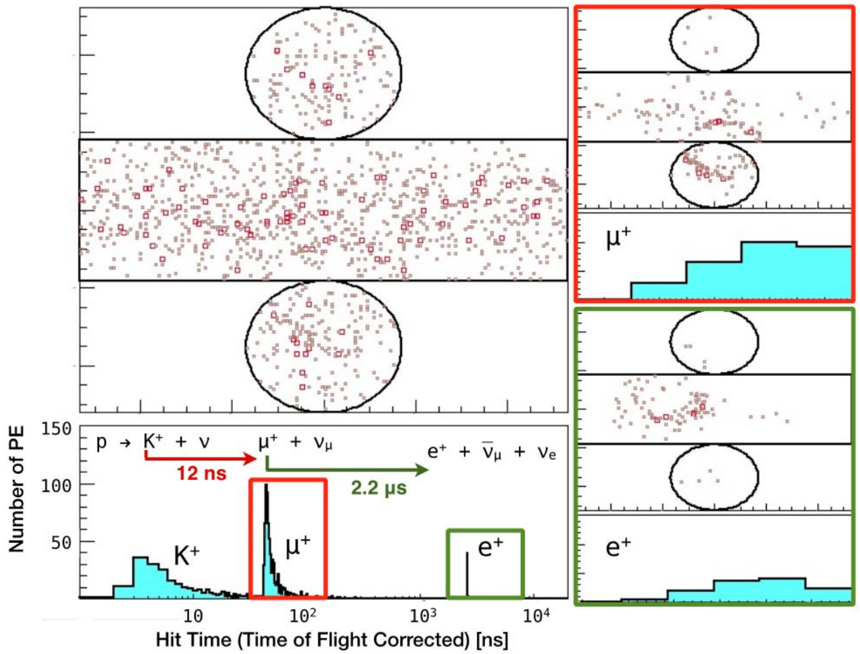


FIG. 2. Level scheme of proton-hole states in ^{15}N and their deexcitation modes. Energies are given in units of MeV. p^* and n^* are the protons and neutrons emitted from the continuum (unbound) region, respectively.

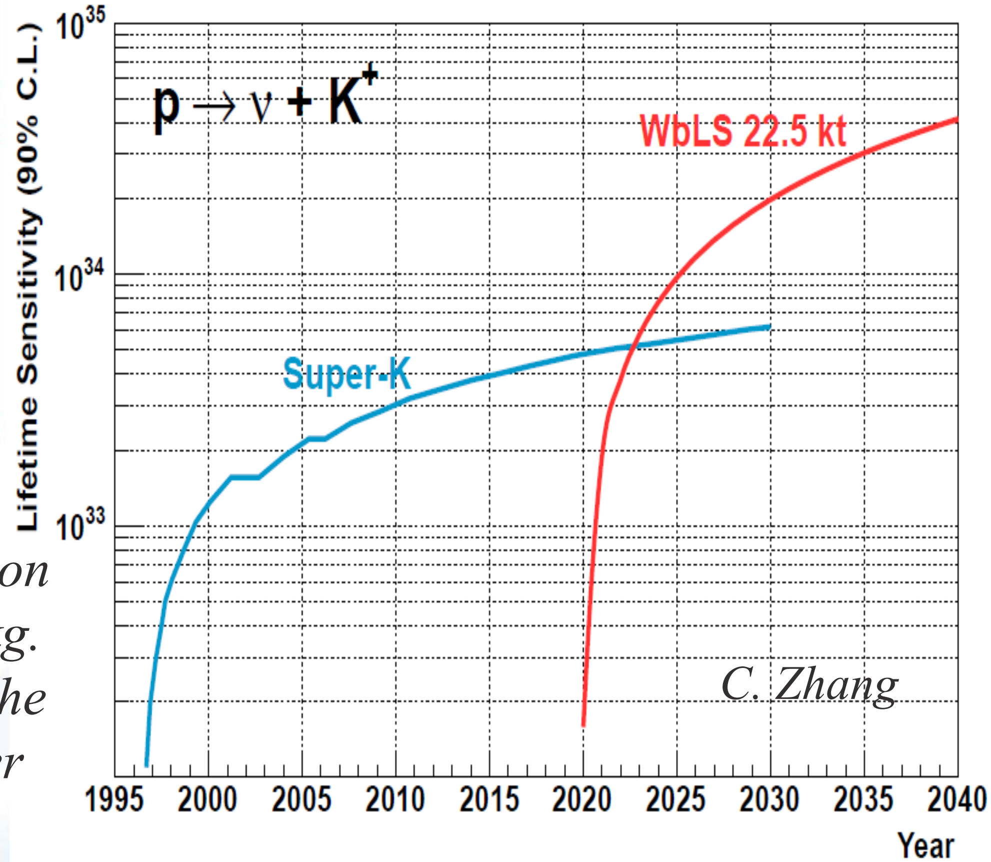
H.Ejiri Phys. Rev. C48 (1993) 1442

Physics below Cherenkov by WbLS

$k^+ \rightarrow \mu^+ + \nu_\mu$ (63.47%)



- *The k^+ decay is now visible.*
- *A new liquid with Scintillation plus Cherenkov = Super-K + LENA?*



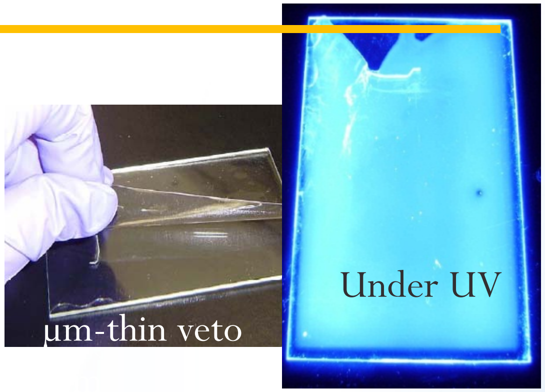
Time and energy cuts give a bkg. rejection efficiency of >99.975%; single-pulse bkg. (μ^+ from ν_μ) can be differentiated from the double-pulse signal (K^+ and its daughter μ^+).

Collide Physics

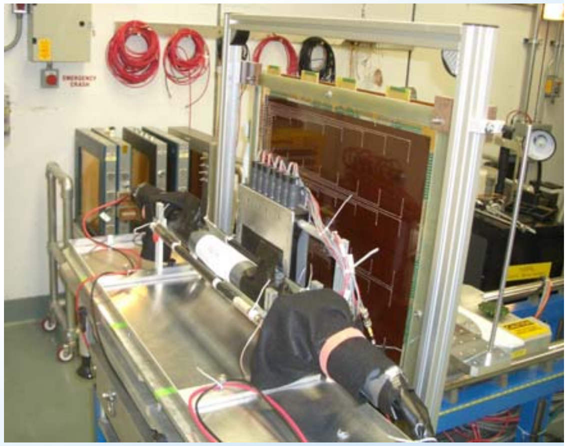
Liquid Scintillator for Energy Frontier

LS Calorimetry R&D

- *Liquid is homogeneous and a suitable option for radiation-harsh environment.*
  - *newly developed LAB-based oil has high f.p. and environmental-safe, higher light-yield with λ>20m; compared to previous 2~3m of CERN-WA-70 or SLIC.*
    R&D: conventional organo-ligand- vs. water-based-loading method for Pb.
- *Performance vs. Cost*
  - *Polycarbonate vs. Teflon (internal light reflection, similar to LENS scintillation lattice prototype at Kimballton).*
  - *Efficiencies at different panel (plate) orientations*
- *Massive total-absorption Calorimetry (with absorber).*
  - *Large water detector is cost effective; but limited energy measurement of hadronic products (below Cherenkov threshold).*
  - *Water-based LS with 90+% of water has the capability of detecting particles below Cherenkov; R&D: 1-m long Teflon-coated aluminum tube is under design and can be stacked at different orientations by different incident particle-beams produced at the NASA space radiation lab.*



Long stability of Teflon film (loaded with LS and fluor); compared to light-sensitive PS+TBP film.



NASA beam setup at BNL. WbLS has been demonstrated to see the light below Cherenkov threshold by intense proton beam

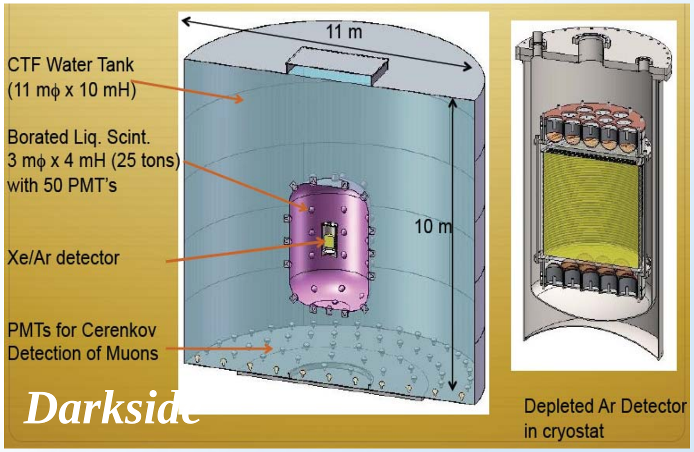
- *Dark Matter*

Liquid Scintillator for Cosmic Frontier

Veto for Dark Matter

- *Radiogenic (purification and controls) and Cosmogenic single-scattered neutrons are the major backgrounds.*
- *With passive shielding:*
  - *40-cm polyethylene + 20-cm Pb + 15-cm Steel:*
  - *~3,000 background events/(ton-yr)*
- *With active (muon) shielding*
  - *1-m liquid scintillator or 5-m water:*
    - *~2 events/(ton-yr)*
  - *1 m ^{10}B-loaded scintillator + 4 m water:*
    - *<0.1 events/(ton-yr)*
  - *5-m liquid scintillator:*
    - *Background is tiny!*

F. Calaprice



- **Current TMB-loaded ^{10}B-LS is not stable (R&D).**

- *Cost-effect for massive detector*
- *Scintillation enhancement of water detector*

Liquid Scintillator for Other Physics

Cost Challenge of NOνA

Physics goals

$\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$

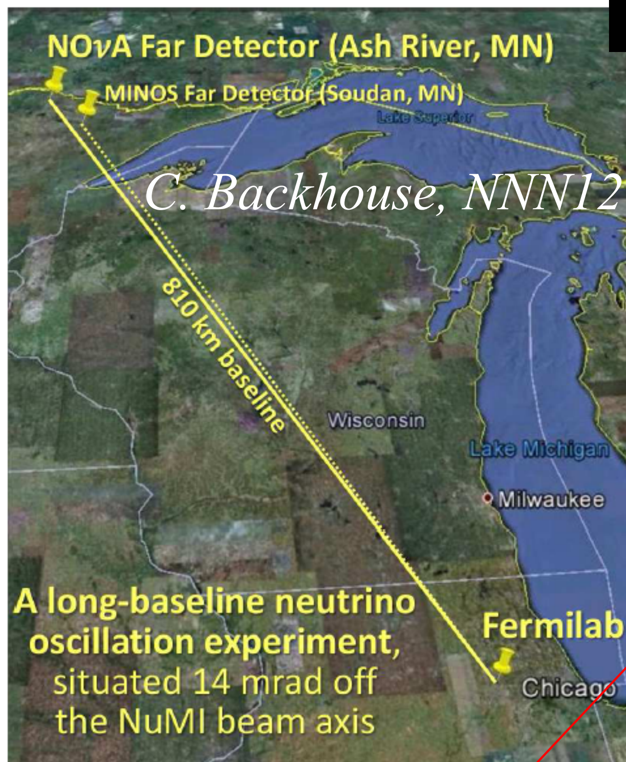
- Measure θ_{13} via ν_e appearance
- Determine the θ_{23} octant
- Determine the mass hierarchy
- Search for $\delta_{CP} \neq 0$

$\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$

- Precision measurements of $|\Delta m^2_{\mathrm{atm}}|$ and θ_{23}
- Could exclude maximal mixing

And...

- Cross-sections from the ND
- Steriles, supernovae, exotica



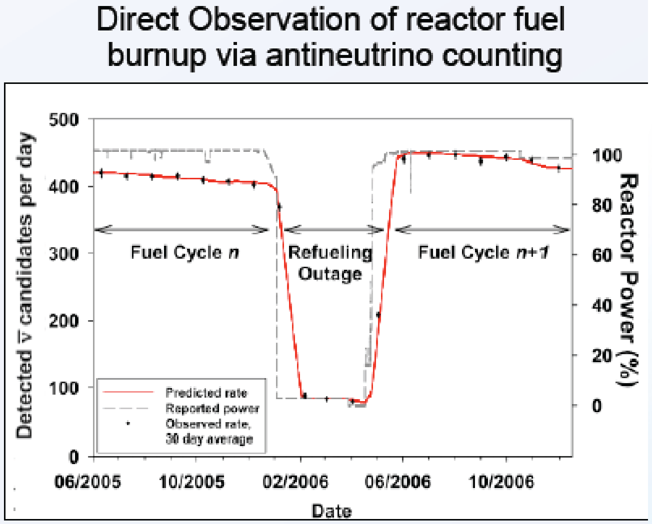
C. Backhouse, NNN12

can we try WbLS in there?

Maury's News:

The 14 kiloton NOvA experiment is finishing the construction of its 5th block out of 28 at the far detector and hopes to start filling soon with scintillator. But the contingency is being used up faster than desirable, and the DOE wants NOvA to identify how to get \$10M more in contingency through some savings, but without giving up detector mass. One idea that has been mentioned is to fill up downstream modules with water and not instrument them, for a mu catcher, but this gives a smaller fiducial volume for electron neutrino identification than just having a smaller detector.

Reactor Monitoring and Safeguard



S. Dazeley, AAP-2012

- *Fuel-burn-up & isotopic compositions*
- *SONGS-type (~25m) with 0.2%Gd-water; a very successful operation over a decade*
- *larger-scale at few Km's (**Watchman**) is a challenge*
    - *Wavelength-shifter*
        - *Amino-G, ~2x; Carbostyril-124, ~4x (SNO)*
- *What about adding (little) scintillator to enhance Gd-capture signal? Water-based LS enhancement! Need engineer study.*

US Liquid Scint. R&D's for Physics Frontiers

	LS R&D	Expt. & Physics
Intensity Frontier		
LBL reactor-ν	*Higher s%, longer λ (new LS?)*	*Daya Bay II, RENO-50 (mass hierarchy)*
SBL reactor-ν	*PSD, loading-^{6}Li*	*ORNL, NIST (anomaly vs. sterile-ν)*
0νββ	*Loading-DBD target by WbLS*	*SNO+ (ν-mass, MH, Majorana vs. Dirac)*
OscSNS	*Loading-in MO*	*ORNL (sterile-ν)*
Proton decay	*mass, cost-effective WbLS deployment*	*Hyper-K, LBNE-II, etc.*
NOνA	*Cost-effective*	*FNAL (water-based LS)*
Other physics	*Purification, engineering studies, etc.*	*nonproliferation, nuclear-fuel monitor, geo-ν, solar-ν*
Energy Frontier	*Loading-Pb & segmentation design; massive WbLS?*	*Collider, accelerator (calorimtery)*
Cosmic Frontier	*veto system, loading-^{10}B*	*Dark Matter (Lux, Darkside)*

Summary

- *LS R&D has been successfully applied to particle physics expt. (e.g. DayaBay & DBD/solar), a transition model in 3 years.*
- *Liquid scintillator continues to be a key element for the next-generation experiments for intensity, energy and cosmic frontiers with different challenges in terms of brighter and optical-cleaner light; plus new metal-loading technologies.*
- *Water-based liquid scintillator, a new detection medium, has been principal- proven of exploring Cherenkov & Scintillation detection; a significant cost-impact for massive detectors (p-decay, NOνA, and other large detectors); need ton-scale demonstration for low-energy detection efficiency and engineering design of circulation system (if need).*
- *Liquid scintillator is the low-cost option for physics frontiers and US has the expertise and facilities to advance this technology; to maintain the leading role in the global competitions.*